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USEFUL STATISTICAL GUIDES AND GRAPHS FOR NEUTRON PROBE SOIL MOISTURE SAMPLING

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Neutron probes are becoming a standard tool for measuring soil moisture. General discussions of the equipment, its operation, and the advantages and disadvantages of its use under a variety of conditions are described in the literature. However, most of these papers treated rather lightly the statistical considerations of neutron probe use.

Functioning of probes depends on the emission of fast neutrons from a radioactive source placed within the soil profile and the subsequent occurrence and detection of slow or thermal neutrons. These slow neutrons are created by the collision of fast neutrons with hydrogen nuclei. Because the bulk of the hydrogen nuclei in soils is contained in the soil water, the rate at which slow neutrons are created is a measure of soil moisture.

The random nature of the radioactive processes upon which the functioning of the probes depends permits the application of probability theory to the problems of determining the statistical reliability of the equipment. Good discussions of the basic statistical considerations useful in radiocounting have been published (Jarrett, 1946,[1/] Kuyper, 1959). However, application of their methods for determining counting error has led to a common misinterpretation of the reliability of soil moisture measurements made with neutron probes. It is apparently a common belief that longer counts must be made at low soil moisture contents than at high soil moisture.

This is not true if the error in terms of soil moisture is considered rather than the error in number of counts (Van Bavel, 1958). A formula for closely approximating the random counting error in terms of soil moisture has been derived by Merriam (1960), and was discussed more fully by Merriam and Knoerr (1961). This formula is based on the fact that the relation between counts per minute and soil moisture percent by volume is essentially linear through the range of soil moisture most commonly encountered.

1/ The author's copy of Jarrett (1946) contains several typographical errors. Caution is necessary in using the formulas as printed without a thorough understanding of their derivation.

A close approximation of moisture percent by volume "Pv" may be made from the equation

$$Pv = \frac{N}{S} \tag{1}$$

where "S" is the calibration curve slope or the change in the counting rate per unit change in Pv, and "N" is the mean counting rate in counts per minute. It should be noted that when a ratio or percent of standard calibration curve is used "S" is the slope of the calibration curve in terms of ratio units per unit change in Pv times the counts per minute of a standard reading. When calibration curves are curvilinear, the slope of the tangent to the curve at the maximum soil moisture to be encountered should be used for "S" in these equations since actual errors will be less than those indicated. Jarrett (1946) gives the equation for the counting rate error "Q" in counts per minute as

$$Q = \pm K \sqrt{\frac{N}{t}} \tag{2}$$

where "K" is the number of standard deviations and "t" is the counting time in minutes. Solving equation (1) for N and substituting in equation (2) the expression for the error, Q becomes

$$Q = \pm K \sqrt{\frac{Pv \cdot S}{t}} . \tag{3}$$

The random counting error "E" in moisture percent by volume is

$$E = \frac{Q}{S} . \tag{4}$$

Substituting the expression for Q from equation (3) in equation (4), we get

$$E = \pm K \sqrt{\frac{Pv}{S \cdot t}} . \tag{5}$$

Selection of Counting Interval

A graph derived from equation (5) showing random counting errors in Pv and in inches of water per foot of soil, for several timing intervals with a neutron probe having a calibration curve slope of 150, has been published (Merriam, 1960) (Merriam and Knoerr, 1961). A more generalized graph, also derived from equation (5), can be used to determine the counting time necessary to obtain various levels of statistical reliability for probes having calibration curve slopes between 150 and 400 (fig. 1). Probability levels are given in figure 1 instead of the appropriate "K" values. The relation between probability and "K" is shown in table 1.

Figure 1 is used in the following manner:

1. Select as a starting point the slope of the calibration curve for the probe to be used.

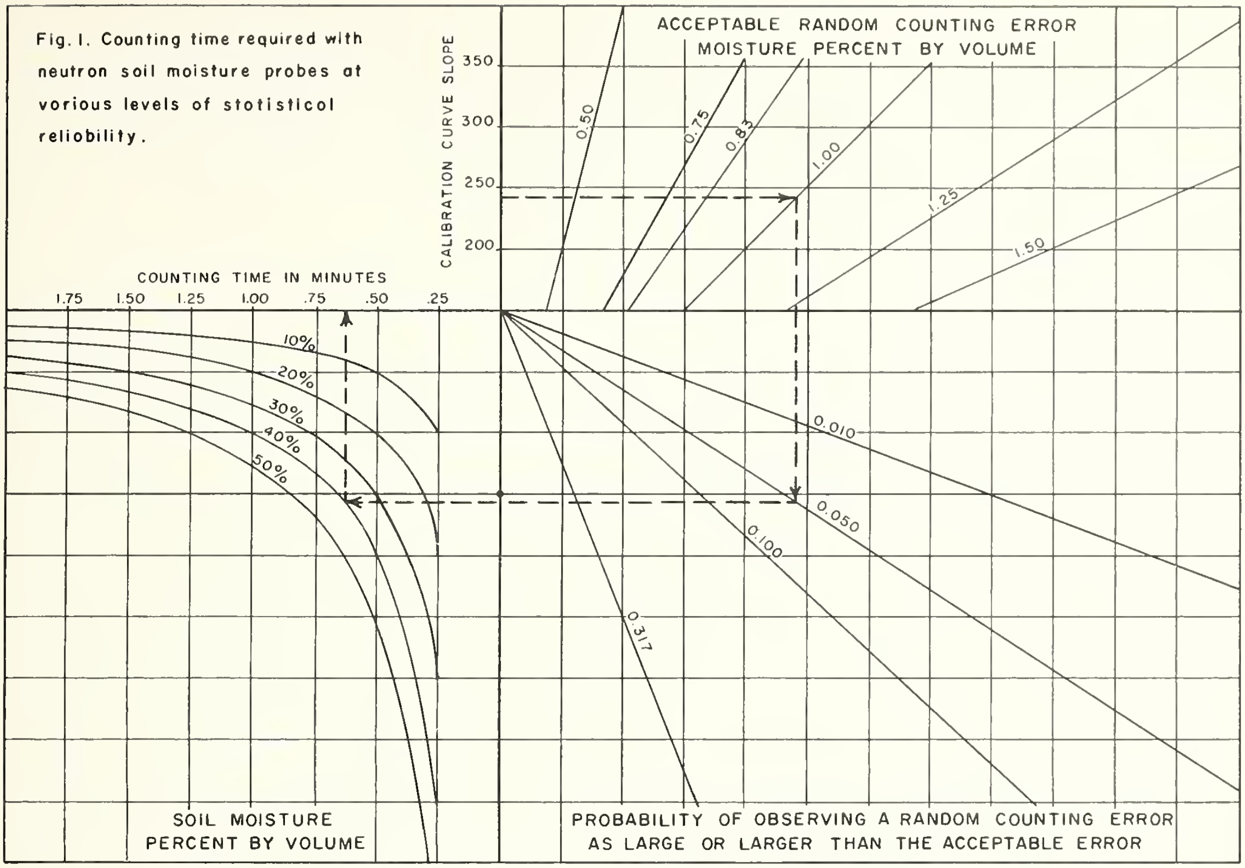

Fig. 1. Counting time required with neutron soil moisture probes at various levels of statistical reliability.

2. Proceed horizontally to the right to the random counting error considered acceptable for the study to be undertaken. Errors from 0.50 to 1.50 percent by volume are given at 0.25-percent intervals. The error at 0.83 percent is also given since this is equivalent to 0.10 inch of water per foot of soil, a reasonable error level for many studies.

3. Proceed vertically downward to the level selected for the probability of equaling or exceeding the acceptable random counting error. Probability levels given are 0.317, 0.100, 0.050, and 0.010.

4. Proceed horizontally to the left to the maximum soil moisture expected to be encountered in the study.

5. Proceed vertically upward to the counting time required.

Figure 1 is not intended as a guide to precise timing interval; rather it should be used to determine the correct order of magnitude of the timing interval. Scalers currently being sold by both major manufacturers of neutron soil moisture probes are supplied with timers that are preset for 2- and/or 1-minute sampling periods rather than variable-time timers. Figure 1 can be used to determine whether more than a single 1-minute sample is needed to satisfy the level of statistical reliability desired for any study.

The selection of the counting time required for the maximum soil moisture expected to be encountered assures that an even greater statistical reliability will be achieved at lower moisture contents. This is due to the direct relation between error in percent by volume and the square root of the soil moisture percent by volume.

Probability of Certain Errors

The relation between random counting errors at several probability levels and soil moisture can be computed from equation (5). Appropriate "K" values are obtained from table 1. Figure 2 shows this relation for a probe having a calibration slope of 239 when a 1-minute timing interval is used.

Table 1.--"K" values for several commonly used probability levels (after Jarrett, 1946)

Probability level	"K"
0.5000	0.6745
0.3173	1.0000
0.1000	1.6449
0.0500	1.9600
0.0100	2.5758
0.0010	3.2905

Essentially, figure 2 can be used to determine the random counting errors expected to be reached or exceeded with this probe 1, 5, 10, 32, and 50 times per hundred counts. Thus at 25-percent moisture a random counting error of 0.83 Pv will be equaled or exceeded only once per hundred counts. Errors of 0.63, 0.53, 0.32, and 0.22 will be equaled or exceeded 5, 10, 32, and 50 times per hundred counts, respectively.

A graph of this nature helps simplify the selection of an acceptable probability level. The 0.10 level is recommended as an adequate level for general radiocounting work (Jarrett, 1946, Kuyper, 1949). The 0.05 and 0.01 levels are commonly used in other statistical work as "significant" and "highly significant" levels. The level selected by the researcher will depend primarily on the nature of his study. Relatively large errors can often be permitted in gross water use studies when a series of measurements is totaled for the moisture content of a soil profile since the positive and negative errors tend to be compensating. Smaller errors may be desirable when studies of moisture changes with time at particular depths are being studied.

It should be noted in connection with figure 2 that the random counting errors at each probability level will be decreased by factors of 0.71, 0.58, and 0.50 for 2-, 3-, and 4-minute counting periods, respectively.

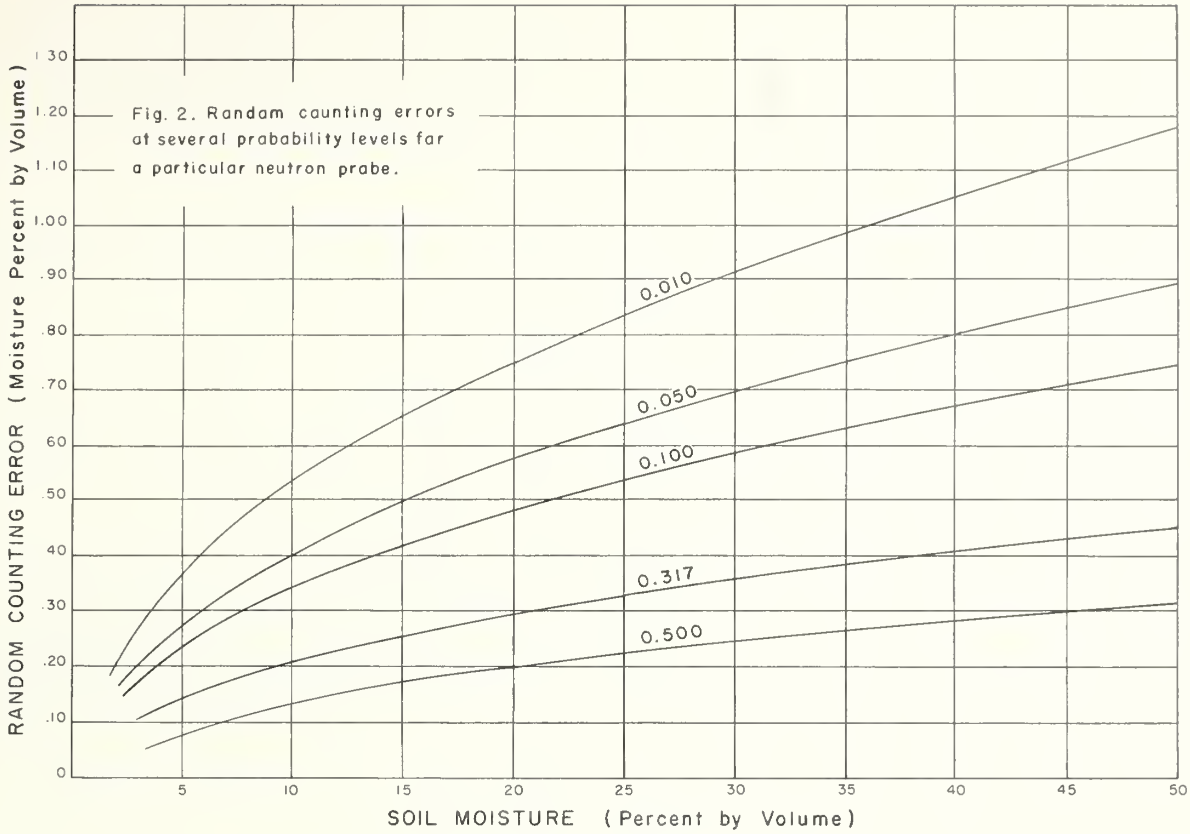

Fig. 2. Random counting errors at several probability levels for a particular neutron probe.

Errors in Timing

The inexact reproduction of timing interval, whether due to automatic timer variations or manual operation of a stopwatch, introduces an additional source of error into soil moisture determinations. For example, a 1-percent timing error at 25 Pv results in a 0.25 Pv error.

Figure 3 illustrates the "maximum probable" total counting error in moisture percent by volume. It can be assumed that when care is used in timing, errors due to timing occur essentially at random. With suitable care, a 0.3 second or 0.5-percent timing error in a 1-minute count should occur no more than about once per hundred counts. If this is true, the probability of encountering a total counting error as large as that indicated by the 0.5-timing error in figure 3 would be 0.0005 since the 0.05 level ($K = 1.96$) was used for the random counting error. "Maximum probable" total counting errors for timing errors of 1.0 and 1.5 percent (if these values are judged to be nearer the 1-percent probability level) are also given.

Random Counting Errors in Analysis of Variance

Stone, Shaw, and Kirkham (1960) showed how the application of basic radio-counting statistics is useful in variance analyses. They determined, among other things, that the error mean square due to repositioning the probe for

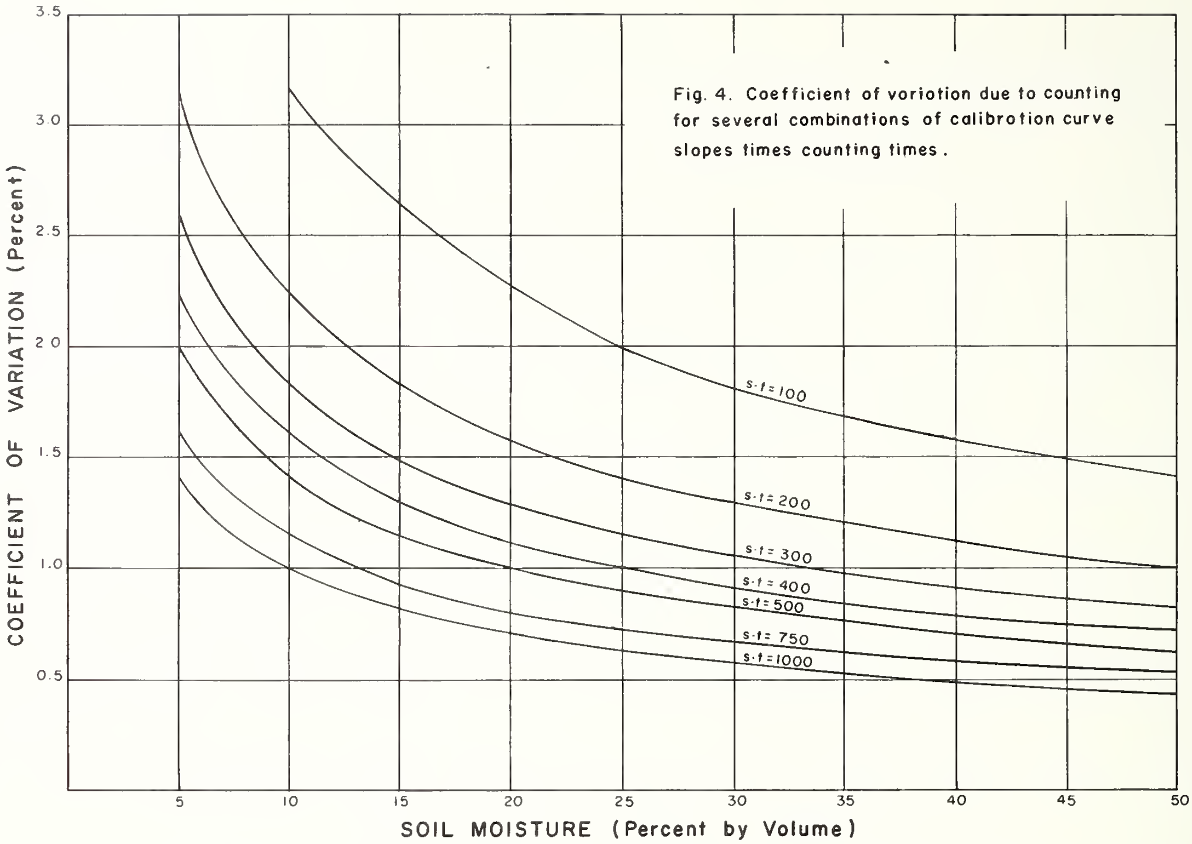

Fig. 4. Coefficient of voriotion due to counting for several combinations of calibrotion curve slopes times counting times.

successive samples at the same point at the same moisture content was of the same order of magnitude as the random counting error expected at that moisture content. Therefore, the errors due to repositioning were exceedingly small. Their technique for this comparison may be summarized as follows:

1. The standard deviation of a single counting determination equals the square root of the number of counts, "n", in the determination.

2. Since "n" is the best estimate of the true number of counts for the sample, the coefficient of variation in percent can be calculated as

$$100 \frac{\sqrt{n}}{n} \quad \text{or} \quad \frac{100}{\sqrt{n}} .$$

This is equal to the "percentage error" when K = 1.0 (Jarrett, 1946).

3. The error mean square in the portion of their analysis discussed above was due to repositioning the probe. The coefficient of variation due to repositioning can therefore be estimated as $100 \sqrt{\text{error mean square}}$ divided by the mean moisture content at the tested position.

In their study the coefficient of variation for repositioning was 3.5 percent. That due to counting was 2.9 percent, indicating that the error apparently due to repositioning was probably largely due to the random counting error.

Similar comparisons may be useful in other variance analyses of soil moisture data. For example, when soil moisture at more than one access tube location is being sampled under similar conditions, the coefficient of variation due to counting at any depth can be compared with that due to replications at the same depth to arrive at a better estimate of variations between tube locations.

Figure 4 has been prepared to provide a rapid estimate of the coefficient of variation due to counting. As previously indicated, the coefficient of variation due to counting may be estimated as

$$\frac{100}{\sqrt{n}} .$$

Since n = N·t and N = Pv·S, the percent coefficient of variation may be calculated as

$$\frac{100}{\sqrt{Pv \cdot S \cdot t}} .$$

Figure 4 was prepared from this relation for several S·t values. For example, the coefficient of variation due to counting at 15 Pv for a 2-minute count with a probe with a calibration curve slope of 225 would be, by interpretation, about 1.22 percent.

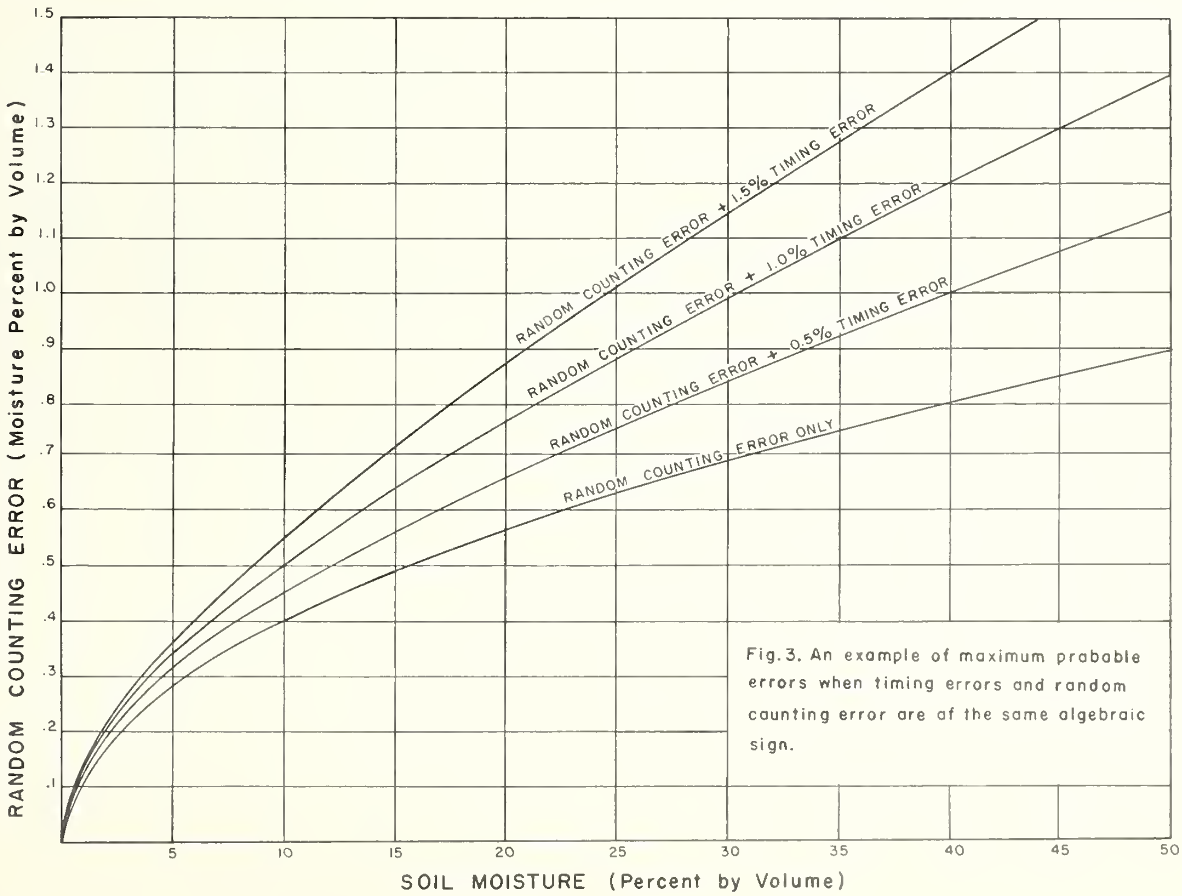

Fig. 3. An example of maximum probable errors when timing errors and random counting error are of the same algebraic sign.

Summary

It is believed that many users and potential users of neutron probes believe in the desirability of longer counting times at low soil moisture than at high soil moisture. This misconception has been nurtured by such statements as "For accurate work at least 20,000 counts should be accumulated" (Nuclear-Chicago, n.d., page 5). This is not true when errors in terms of soil moisture are considered rather than errors in counting rate.

A coaxial graph (fig. 1) permits the determination of the counting time necessary to satisfy the levels of statistical reliability selected by the researcher at soil moisture contents up to 50 percent by volume for probes having calibration curve slopes between 150 and 400 counts per minute per unit moisture percent by volume.

A graph (fig. 2) illustrates the relation between random counting errors at several probability levels and soil moisture. Figure 3 illustrates the magnitude of total counting errors when timing errors and random counting errors are of the same algebraic sign.

The coefficient of variation due to counting and its application in variance analyses are briefly discussed. A graph (fig. 4) for estimating the coefficient of variation due to counting for several combinations of calibration curve slope times counting time is given.

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